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THE NATURE OF UNCERTAINTY

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# THE NATURE OF UNCERTAINTY

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To help set the stage for our seminar the chairman has asked
me to comment briefly on the nature of uncertainty. Initially, I
shall do this by outlining some of the dimensions of the problem
in general. Later, I shall focus more on the context of resource
analysis.

Let us start out by making a distinction between risk and
uncertainty.[**] In a risky situation we know the objective probability
distribution of the random event involved in the problem. In situa-
tions of uncertainty we do not know anything about the objective
probabilities involved, and hence the problem must be dealt with in
terms of subjective considerations -- either formal or informal.

Sometimes this distinction is made in different terms; e.g.,
"risk" is called statistical uncertainty, and "uncertainty" is called
state-of-the-world or requirements uncertainty.[***] The relative im-
portance of these categories depends very much on the context of the
problem at hand. For instance in most long range planning problems,
state-of-the-world uncertainty tends to dominate statistical uncer-
tainty (risk). This, of course, has important implications for
choosing the appropriate concepts and methods for dealing with
uncertainty.

Another dimension of the nature of uncertainty pertains to what
may be called the life cycle context. That is to say, the nature of

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[**] E.g., see Albert Madansky, "Uncertainty," Chapter 5 in E. S.
Quade and W. I. Boucher, Systems Analysis and Policy Planning (New
York: American Elsevier Publishing Co., Inc., 1968), pp. 81-96.

[***] Examples of the latter are uncertainty about strategic con-
text, technological uncertainty, and uncertainty about the enemy and
his potential actions and reactions.

uncertainty depends very much on what phase of the weapon system life
cycle the issue up for decision stems from; e.g.:

> Pre-R&D
> Early R&D
> Late development
> Production
> Operation.

Clearly "state-of-the-world" uncertainties dominate the pre-R&D
phase. This may or may not be so in the case of current operations.
However, even here if radically new operational concepts are being
considered, much more than "statistical uncertainty" may be involved
in the problem.

Still another dimension of the nature of uncertainty is related
to the level of sub-optimization being considered in the decision
problem at hand -- in short, the "analytical context." At one ex-
treme is the "total force" context; e.g., the total USAF force struc-
ture, or the total DOD.[*] At the other extreme is a component of an
individual weapon system -- e.g., the major hardware, or some sub-
component like the propulsion sub-system. In between is the indi-
vidual weapon system context. Obviously, the nature of the uncer-
tainty problem is quite different depending upon which of these
contexts fits the problem at hand.

Let us turn now to a brief discussion of the types of methods
that may be used to deal with uncertainty. Since these should be
familiar to most of you, I shall comment only briefly on each one.
The following is a representative list -- though certainly not a
complete one -- and the order is not necessarily in accordance with
relative importance:

1. Monte Carlo: a technique for reckoning with statistical
   fluctuations by drawing random samples from a carefully
   determined distribution.[**] It is most useful in dealing

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[*] Another "total force" context -- perhaps more interesting than
the ones mentioned above -- is the total force in some mission area.
An example would be the total strategic force made up of Army, Navy,
and USAF weapon systems and related support.

[**] For a good brief discussion of the technique, see E. S. Quade
(ed.), Analysis for Military Decision (Chicago: Rand McNally & Co.,
1964), pp. 240-243.

with situations of risk or statistical uncertainty. However, it is sometimes used in other situations where subjective probability distributions are substituted for objective ones.[*]

2. A fortiori analysis: in comparative studies the systems analyst may resolve all major uncertainties in favor of the alternatives to the intuitively preferred solution. If the latter holds up well in such a comparison, the analyst has a powerful argument in favor of the intuitively preferred alternative.

3. Sensitivity analysis: in various types of analytical studies, rather than merely settling for "expected values," the analysts may vary the values of key uncertain parameters or assumptions over their relevant ranges to see what the impact is on final outcomes (e.g., ranking of alternatives).[**] This can be very useful to decisionmakers in deciding about which uncertainties are really important and hence are candidates for further deliberation -- e.g., seeking ways to reduce or hedge against these uncertainties.[***]

4. A "range of estimates": in a sense this is a special case of (3) above. Here, in addition to an "expected value" case, several other outcomes are calculated corresponding to alternative assumptions about how key uncertainties are resolved.[+] One mode that is often used is the range of

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[*] E.g., see P. F. Dieneman, Estimating Cost Uncertainty Using Monte Carlo Techniques, RM-4854-PR (Santa Monica, Calif.: The Rand Corporation, January 1966).

[**] For a discussion of cost sensitivity analysis, see G. H. Fisher, Cost Considerations in Systems Analysis (New York: American Elsevier Co., Inc., 1971), pp. 215-217.

[***] A special case of sensitivity analysis is the so-called "breakeven" analysis. Here, in the case of a very key parameter about which we are uncertain, the analysts can calculate that value of the parameter which must be assumed in order to change the ranking of the most important alternatives being considered.

[+] For this technique to be useful to decisionmakers, the alternative assumptions must be set forth explicitly.

estimates characterized by "high," "medium," and "low."

5. <u>Supplemental discounting</u>: analysts very often use the process of discounting future cost and benefit streams to equalize them with respect to time preference. Advocates of supplemental discounting suggest that an <u>additional</u> rate be applied to allow for uncertainties about future technology, the enemy threat, etc. Most analysts today prefer to distinguish between discounting for time preference and for uncertainty; and in general they prefer to treat uncertainty as an explicit problem in the systems analysis process, and not through the use of an aggregate supplemental discount factor.

6. <u>Adjustment factors</u>: the use of "adjustment factors" to allow for requirements uncertainty has been advocated primarily for application in cost analyses of future major equipment proposals.[*] It is argued that because of uncertainties about technology and state-of-the-art advances, etc., cost estimates made during the early stages of the hardware development cycle should be adjusted upward by using "average factor increases" derived statistically from historical records.

7. <u>Special studies</u>: very often systems analysts can be of considerable help to the decisionmakers by conducting special studies to explore the benefits and costs of various strategies for hedging against uncertainty in some particular area, to examine the benefits and costs of "buying time" in order to gain more information and hence reduce uncertainty, etc.

So much for concepts and methods for dealing with uncertainty. Let us now change gears slightly and consider some of the implications

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[*] E.g., see Robert Summers, <u>Cost Estimates as Predictors of Actual Weapon Costs: A Study of Major Hardware Articles</u>, RM-3061-PR (abridged) (Santa Monica, Calif.: The Rand Corporation, March 1965).

of the preceding discussion.  We shall start by considering the follow-
ing question:  Given the dimensions of the nature of uncertainty out-
lined above, and given the types of concepts and methods for dealing
with uncertainty, what are the implications for the development of
analytical tools and techniques?

Clearly, the list of implications is a long one.  However,
because of time constraints, I can only present a few examples to
serve as illustrations.  I am sure that most of you in the audience
can easily extend the list in your own minds.

1.  If we are systems cost analysts serving the "pre-R&D"
    planning process, we no doubt will have to help the decision-
    makers grapple with state-of-the-world ("requirements")
    uncertainty.  One of the main ways to do this is to engage
    in a considerable amount of ingenious sensitivity testing.
    But in order to do really effective cost sensitivity analy-
    sis, we have to have good parametric cost models[*] -- models
    for individual systems, sub-systems, and force mixes (e.g.,
    an inter-service strategic force mix cost model).  While
    much progress has been made in recent years in developing
    good parametric cost models, much more remains to be done.  I
    would say that the effectiveness of our ability to deal sub-
    stantively with problems of uncertainty is directly related
    to the availability of a wide range of well-designed parametric
    cost models.[**]

2.  If we are dealing with an individual total weapon system
    context, and we are required to treat the problem of sta-
    tistical uncertainty (or risk) in the cost estimates, the

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[*] A parametric cost model is one that is "open-ended" with respect
to key cost-generating explanatory variables such as major equipment
performance characteristics, operational concepts, deployment, force
size, etc.  For an example, see the hard point defense cost model pre-
sented in Chapter 7 of my Cost Considerations in Systems Analysis.

Parametric cost models are also very useful in doing a fortiori
analysis, break-even analysis, etc.

[**] However, as I shall indicate shortly, parametric models cannot
do the entire job.  Important supplementary measures must usually be
employed.

Monte Carlo technique may be appropriate. However, most
past and current applications have certain deficiencies.
One stems from the fact that in many instances the individual
elements of weapon system cost are assumed to be independent,
when in reality they are not. Thus, we need ways to take
into account the interdependencies.* More important, perhaps,
is that in most applications the cost analysts use their in-
tuition to make assumptions about the probability distributions
for the various elements in total system cost. In many cases
it is not clear that the analysts have sufficient substantive
knowledge in specific areas to make meaningful subjective
probability specifications; and as a result, some critics
question the value of a distribution of weapon system total
cost derived by Monte Carlo procedures as practiced to date.

3. As a final example let us take the context of hardware cost
analysis where we have to make cost estimates for a new ad-
vanced major equipment item that would be operational many years
from now. In problems like this we are usually faced with
substantial technological and manufacturing state-of-the-art
uncertainties. While statistically-derived parametric cost
models can help considerably in dealing with these problems,
they can only take us so far. One of the main reasons is that
they are derived from an historical data base that does not
include the advanced equipment item under consideration.
Thus, the use of parametric cost models has to be supplemented
by the results of special studies. For example, the analysts
may have to go to various government and contractor facilities
where experiments are being conducted on new materials, manu-
facturing techniques, prototype sub-systems, and the like.
Information gained from such field work, even though some of it
may be qualitative, can be of great help in establishing mean-
ingful ranges of cost estimates for the advanced hardware item
under consideration.

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I understand that some work along this line is currently under
way.

As a final topic, I would like to consider briefly a few points
pertaining to the implications of the preceding discussion for DOD
policy:

1. Can we somehow maintain ranges of cost estimates in the
   "DOD books," rather than just point estimates? Probably
   not, when the context is the conventional budget. But in
   the planning and programming realms, having a range of
   estimates for DOD in-house use would seem feasible and
   desirable -- especially for important major parts of the
   defense program.*

2. Related to (1) is the matter of "advocacy cost estimates."
   I have been led to believe that because of new DSARC pro-
   cedures this is no longer the problem it once was. But to
   the extent that advocacy estimates are still developed and
   used, DOD policy should require that for "in-house" DOD
   use other (presumably more realistic) estimates be avail-
   able "in the system," so that decisionmakers will have
   alternative sources of information rather than merely the
   advocacy source.**

3. We must continuously watch the allocation of DOD's ana-
   lytical resources between the development of formal quanti-
   tative methods for dealing with uncertainty (usually sta-
   tistical uncertainty) on the one hand, and the conduct of
   ad hoc special studies to help deal with state-of-the-world

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\* Here, proper documentation is important. It is not sufficient
to merely have a range of numbers "in the books." In addition, each
case must be supplemented with explicit descriptions of the key
assumptions underlying each particular estimate in the range. Purely
quantitative treatments are not enough.

\*\* Use of advocacy estimates inevitably leads to unreal and un-
necessary "uncertainty." Because use of advocacy estimates almost
by definition means there will be substantial (often huge) "cost
growth," some people observing the process might conclude that the
early estimates were made under conditions of more real uncertainty
than was actually necessary. Alternative sets of early estimates
could have exposed the advocacy estimates for what they in fact were.

("requirements") uncertainty on the other.* While both
types of effort are needed and should be pursued, I sometimes
feel that more effort (including travel budget) should be
allocated to the special study efforts. This is especially
true if uncertainty is to be dealt with adequately in "design-
to-cost" deliberations. Here, as in most cases, parametric
methods derived from historical data bases will not do the
total job. They must be supplemented by the results of
special studies.

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*As I indicated previously such special study efforts can be
directed toward assisting decisionmakers in considering the costs
and benefits of buying more information, of keeping options open, of
pursuing parallel exploratory development efforts, etc.